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(71) Applicant *(for all designated States except US)*: **TELE-COM ITALIA S.p.A** [IT/IT]; Piazza degli Affari, 2, I-20123 Milano (IT).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **CAPONI, Renato** [IT/IT]; Telecom Italia S.p.A., Via G. Reiss Romoli, 274, I-10148 Torino (IT). **POTENZA, Marcello** [IT/IT]; Telecom Italia S.p.A., Via G. Reiss Romoli, 274, I-10148

Torino (IT). **BOCCATO, Diego** [IT/IT]; Telecom Italia S.p.A., Via G. Reiss Romoli, 274, I-10148 Torino (IT). **SCHIANO, Marco** [IT/IT]; TELECOM ITALIA S.p.A., Via G. Reiss Romoli, 274, I-10148 Torino (IT).

(74) Agents: GIANNESI, Pier, Giovanni et al.; Pirelli S.p.A., Viale Sarca 222, I-20126 Milano (IT).

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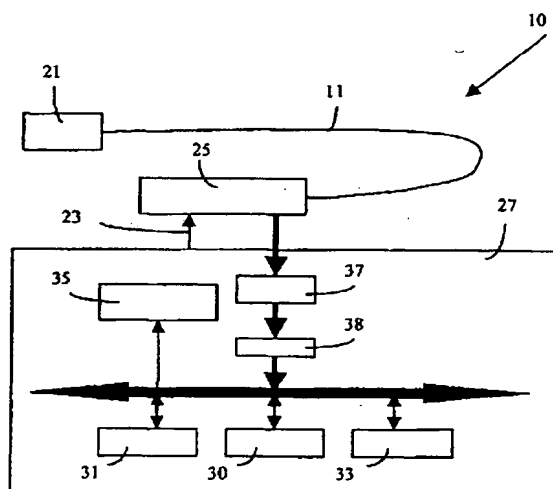
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(54) Title: METHOD, SYSTEM AND DEVICE FOR MEASURING THE POLARISATION MODE DISPERSION OF AN OPTICAL FIBRE

(57) Abstract: The present invention relates to a new model for interpreting interferometric measurements, able to lead to a new method, system (10) and device (27) for measuring the PMD (Polarisation Mode Dispersion) of an optical fibre (11). The model, which is based on the theory of propagation of the optical signal as can be determined according to the so-called Principal States of Polarisation (PSPs) of the fibre, leads to a new interpretation of the interferogram generated with the interferometric measurements and is characterised in that it identifies in said interferogram a central peak and two side lobes. Thanks to this new model, it is possible to determine the PMD of the fibre based on the information content associated to at least one of the two side lobes identified in the interferogram.

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"Method, System and Device for Measuring the Polarisation Mode Dispersion of an Optical Fibre"

TECHNICAL FIELD

The present invention relates to a method for measuring
5 the Polarisation Mode Dispersion or PMD of an optical
fibre, to the system able to allow its application and to
the device able to perform the PMD measurements according
to said method.

BACKGROUND ART

10 As is well known, polarisation mode dispersion is a
phenomenon of distortion of the optical signal that
propagates in single mode optical fibres, i.e. optical
fibres that carry signals in a fundamental propagation mode
constituted by a pair of degenerate modes with orthogonal
15 polarisation.

This phenomenon is, as is well known, linked to the dual
degeneration of the fundamental mode of the optical fibres.
Construction imperfections in real fibres (core
ellipticity, external stresses, etc.) entail different
20 group velocities for the two degenerate modes of the
optical signal transmitted at one end of the fibre and
hence distortions of the signal received by a receiving
device (receiver) located at a second end of the fibre.

Therefore, it is important to develop accurate techniques
25 for measuring PMD to characterise, for example,
telecommunication systems that use optical fibres to carry
signals, in particular in the case of high speed or high
capacity transmission systems, for instance at bit rates up
to 10 Gbit/sec or higher.

30 The PMD of the fibres is measured, for instance, by
connecting a segment of optical fibre (fibre) 11 to be
characterised to appropriate measuring instruments or
devices 10 (Fig. 1).

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The paper "Polarization Mode Dispersion of Short and Long Single-Mode Fibers" by N. Gisin et al, published on the "Journal of Lightwave Tech." Vol.9 on 7 July 1991 discloses, for instance, an instrument 10 for measuring the
5 PMD, which comprises an optical source 21 (Fig. 1, Fig. 2), able to generate optical signals to be applied to the fibre 11, a Michelson interferometer (interferometer) 25 connected to the second end of the fibre 11, able to apply Differential Group Delays or DGD to the received optical
10 signal and, at the output of the interferometer 25, a measuring device 27 able to convert the optical signals into electrical signals and to process, on the basis of program modules stored therein, the electrical signals received.
15 According to the prior art, the electrical signals obtained downstream of the interferometer 25 are graphically represented by the measuring device 27 by means of an interferogram having in its x-axis time offset values introduced by the interferometer and in its y-axis values
20 of intensity of the photo-current generated.
In particular, according to the mentioned paper, said interferogram is to be interpreted as a Gaussian distribution of PMD of the fibre, so that the PMD itself can be determined according to the standard deviation of
25 the Gaussian curve that best interpolates the interferogram.
This type of interpretation of the electrical signals derives from the fact that to the fibre 11 is applied a propagation model called "waveplate model", which consists
30 of considering the real optical fibre as a great number of birefringent plates positioned in cascade with respect to each other and having their main axes oriented randomly.

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This model is used, as is well known, to assess signal time-of-flight, in the hypothesis that at each interface between a waveplate and the next one the optical signal is coupled randomly on the main axis of the downstream

5 waveplate.

Based on the known model and in the realistic hypothesis that the length of the fibre is far greater than the coupling length between the polarisations, the prior art concludes that the measured graphic representation

10 corresponds to a Gaussian curve with a standard deviation equal to twice the standard deviation of the optical signal due to PMD and hence indicative of the PMD of the fibre.

However, it is believed that the measurements obtained taking the known model as a reference do not precisely

15 correspond to real PMD values.

In essence, it is believed that the conclusions of the prior art, which are based on the identification of the distribution of the times-of-flight of the optical signal with the distribution of the electrical field are wrong.

20 It is also believed that the PMD measurements obtained according to the known model are consequently only approximately correct.

DISCLOSURE OF THE INVENTION

The technical problem the present invention aims to

25 tackle is to determine a new propagation model of the fibre that will lead, in the first place, to a new method for measuring the fibre PMD that is more realistic under all computational conditions.

The present invention therefore aims to solve the above

30 technical problem by means of a new model for interpreting the interferogram and consequently a new method, system and device for determining the PMD of the fibre, as claimed.

In particular, the new model which is based on the theory of propagation of the optical signal as can be determined according to the so-called Principal States of Polarisation (PSPs) of the fibre, leads to a new
5 interpretation of the interferogram, characterised by the identification in said interferogram of a central peak and two side lobes.

Thanks to this new model, it is possible to determine the PMD of the fibre on the basis of the information
10 content associated with at least one of the side lobes identified in the interferogram.

BRIEF DESCRIPTION OF THE DRAWINGS

This and other characteristics of the present invention shall become readily apparent from the following
15 description of a preferred embodiment, provided purely by way of non limiting example with the aid of the accompanying drawings, in which:

Fig. 1 shows a general measurement layout that uses the interferometric method (IM);
20 Fig. 2 shows a block diagram of the system of Fig. 1;

Fig. 3 shows a general diagram of the model of the optical source constituting the basis of the method according to the invention; and

Fig. 4 shows an example of the results obtained with the
25 method according to the invention.

DESCRIPTION OF A PREFERRED EMBODIMENT

With reference to Fig. 2, the instrument or system for measuring the PMD able to use the interferometric method (measuring system or apparatus IM) 10 comprises, in
30 particular, an interferometer 25 and a measuring device 27 connected at the output of the interferometer 25 itself and able to control its operation, in known fashion, by means of a control connection 23.

The measuring device 27 comprises, for instance, a control unit (CPU) 30, a read-only memory unit (ROM) 31 and a random access memory unit (RAM) 33, all known and connected to each other in known fashion by means of a

5 data, control and command channel (BUS).

The measuring device 27 further comprises a display device (display) 35, known in itself, and an opto-electronic module 37 associated to an amplifier 38, respectively able to convert the optical signals coming from the

10 interferometer 25 into electrical signals and to amplify them; the display 35 and the amplifier 38 are connected, in known fashion, to the BUS.

The ROM 31, according to the present invention, comprises program modules developed when designing the measuring

15 system 10 and able to implement the method according to the invention, as will be described in detail farther on.

Said program module, as will be readily apparent to a person versed in the art, can also be stored in the RAM 33 by means of reading devices, not shown in the figure, able

20 both to read from appropriate computer products the program modules according to the invention and to store said program modules in the RAM 33 itself.

With reference to the measuring system 10, the method according to the present invention is based on the

25 hypothesis of broad band radiation with spectral components that propagate according to the theory of the Principal States of Polarisation (PSPs).

In particular, with reference to the measuring system 10, the method according to the invention is based on the

30 following interpretative model and the corresponding logical-mathematical passages:

   (a) the spectrum of the (incoherent) optical source is approximated in segments by a family of rectangular

spectral intervals with extension Δv (Fig.3), each described by its amplitude, by its random polarisation state and by a phase factor, which is also stochastic;

5　(b) the spectral width of the interval is specified relative to the band of the PSPs and to the bandwidth of the amplifier 38, in order to obtain a reasonably accurate approximation of the spectrum of the optical source 21,

10　(c) a statistical description of optical propagation inside the fibre being measured is used, in terms of *ensemble* of spectral intervals defined above, *ensemble* that excites a statistical set of PSP,

(d) the output spectrum of the signal is thereby
15　obtained, which comes to depend on a set of statistical parameters: amplitudes of projection on the PSP and on the axes of the polarisation analyser, values of DGD and phase factors;

(e) the interferometric photo-current is expressed
20　according to the power spectrum of the optical source 21 and of the density of probability of the DGD determined by the PMD of the fibre 11.

The result obtained at passage (e) represents one of the characteristic elements of the present invention and is
25 applied to implement the method according to the present invention.

In particular, based on the proposed model, illustrated in Fig. 3, the spectrum $S_{in}(v)$ of a randomly polarised source is subdivided $M - N$ rectangular spectral intervals $S_e(v)$
30 having width Δv and amplitude U_n according to the following mathematical expression:

$$S_{in}(v) = \sum_{n=N}^{M} U_n \mathbf{p}_n S_c(v - n\Delta v)e^{j\phi_n} \qquad (1)$$

Each replication translated in frequency of the fundamental interval has a polarisation state and a phase factor represented by statistical vectors $\mathbf{p}_n$ and by independent

5 stochastic variables ϕ_n.

The choice of spectral width Δv is constrained by two extremes of a physical nature. The *upper limit* for Δv is the minimum band of the PSPs in the spectral domain of the optical source 21 (Fig.2, Fig.3), since the assumption is

10 that every spectral interval propagates according to the model of the PSPs at the first order. This upper limit is, as is well known, in the order of the inverse of the average DGD for the fibre being measured and it falls within the GHz range even for values of *DGD of tens of*

15 *picoseconds.* On the other hand, the *lower limit* for Δv is imposed by the opto-electronic module 37 and by the amplifier 38 which, as is well known, has a limited band, as set out in detail hereafter and it can fall in the range of hundreds of kHz.

20 A value of Δv selected within the frequency domain identified by said upper and lower limit is to be considered suitable for an *approximation in rectangular segments* and sufficiently accurate for all LED optical sources commonly used in IM apparatuses (10); moreover,

25 this conclusion confirms that the approximation proposed in the mathematical expression (1) has correct physical foundations.

The set of spectral intervals $\{U_n S_e(v - n\Delta v)\}$, after being launched in the fibre 11, excites a set of PSP pairs,

30 each characterised by the value $\Delta \tau_n$ of DGD. At the input end of the fibre, the elementary spectral intervals are

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projected on the slow and fast PSP, respectively with amplitudes $\sqrt{\alpha_n}$ and $\sqrt{1-\alpha_n}$; in which α_n represents the power coupling coefficient between the nth interval and the axis associated with the corresponding fast PSP.

In similar fashion, at the output of the fibre 11, the coefficients of projection of the output PSPs on the axis of polarisation of the interferometer are indicated as $\sqrt{\beta_n}$ and $\sqrt{1-\beta_n}$. The spectrum of the signal after the latter selection in polarisation is then expressed in the form:

$$S_{out}(\nu) = \sum_{n=N}^{M} a_n U_n S_e(\nu - n\Delta\nu)e^{-j2\pi n\Delta\tau_n/2}e^{j\phi_n} + \sum_{n=N}^{M} b_n U_n S_e(\nu - n\Delta\nu)e^{j2\pi n\Delta\tau_n/2}e^{j\phi_n} \qquad (2)$$

in which, for the sake of convenience, the two new statistical variables $a_n = \sqrt{\alpha_n \beta_n}$ and $b_n = \sqrt{(1-\alpha_n)(1-\beta_n)}$ have been introduced.

The average value of the DGD of the PSP was neglected, referring the quantities $\Delta\tau_n$ to the origin of the delays set at the interferometer.

Since in the time domain, as is well known, the interferometric photo-current I is proportional to the auto-correlation function of the output signal, in the frequency domain the quantity to be computed is the power spectrum $|S_{out}(\nu)|^2$:

$$I(\nu) \propto S_{out}(\nu) \cdot S_{out}^*(\nu) =$$
$$= \left(\sum_{n=N}^{M} a_n U_n S_e(\nu - n\Delta\nu)e^{-j2\pi n\Delta\tau_n/2}e^{j\phi_n} + \sum_{n=N}^{M} b_n U_n S_e(\nu - n\Delta\nu)e^{j2\pi n\Delta\tau_n/2}e^{j\phi_n} \right) \cdot (c.c.)$$

$$(3)$$

relationship in which 'c.c' indicates the complex conjugated expression of the term in round parentheses.

According to the present invention, it is hereby demonstrated that the interference between different

spectral intervals $S_e(v-n\Delta v)e^{j\phi_n}$ does not give rise to any significant contribution to the photo-current and therefore can be neglected.

For this purposes, the expression of the photo-current generated by the opto-electronic module (detector) 37 and by the amplifier 38 shall now be discussed in detail, with particular reference to the band limitation of the detector 37 and of the amplifier 38.

The module of the field incident on the opto-electronic module 37 has, as is well known, the following expression:

$$E_P(t,T) = \frac{1}{2}[E_{IN}(t) + E_{IN}(t+T)] ,$$

in which $T = 2\frac{n}{c}(L_1 - L_2)$ is the delay introduced by the offset of the interferometer, E_P (t, T) is the electrical field incident on the opto-electronic module 37 and E_{IN} (t) is the electric field of the signal at the output of the fibre.

It should be noted that all signals depend on two variables: the variable t is the time variable whereon the signals are measured, with a domain coinciding with the time interval of the measurement (typically a few seconds). The variable T is, as stated, the delay introduced by the offsetting of the interferometer 25, with a domain that coincides with the DGD interval of interest, typically [0.1, 100] ps. The quadratic photo detection and electrical amplification process is characterised, neglecting the conversion constants of the physical magnitudes, by the following relationships between the signals:

$$I_R(t,T) = E_P^2(t,T) = \frac{1}{4}[E_{IN}(t) + E_{IN}(t+T)]^2 = \frac{1}{4}[E_{IN}^2(t) + E_{IN}^2(t+T) + 2E_{IN}(t)E_{IN}(t+T)]$$

$$I(t,T) = I_R(t,T) * h(t) = \frac{1}{4}[E_{IN}^2(t) + E_{IN}^2(t+T) + 2E_{IN}(t)E_{IN}(t+T)] * h(t)$$

in which $I_R(t, T)$ is the current generated by the opto-electronic module 37 and sent to the amplifier 38, $I(t, T)$ is the current at the output of the amplifier 38 and $h(t)$ is the impulse response of the amplifier 38 with limited

5 band, which naturally depends only on the variable t.

Recalling that the signals $E_{IN}(t)$ and $E_{IN}(t+T)$ are at optical frequencies and that no electrical amplifier is capable of following their variations, one obtains:

$$I(t,T) = I_R * h(t) \propto \left\langle E_{IN}^2(t) \right\rangle_{1/B} + \left\langle E_{IN}^2(t+T) \right\rangle_{1/B} + 2 E_{IN}(t) E_{IN}(t+T) * h(t)$$

10 in which the symbol $< >_{1/B}$ indicates the time average computed over an interval in the order of the reciprocal of the band of the amplifier 38.

Since the continuous component does not carry the information and is suppressed by the measuring instruments

15 of the PMD, it is best to consider only the alternate component of the previous signal:

$$I_{AC}(t,T) \propto E_{IN}(t) E_{IN}(t+T) * h'(t)$$

in which the spectrum of $h'(t)$ coincides with that of $h(t)$,

20 except in the origin where it is zeroed.

In the frequency domain, computing the Fourier transforms with respect to the variable t, one obtains:

$$\tilde{I}_{AC}(f,T) \propto [\tilde{E}_{IN}(f) * \tilde{E}_{IN}(f) e^{j2\pi fT}] \cdot \tilde{H}'(f) \qquad (4)$$

It is readily apparent that the spectral components of the

25 convolution in parentheses that exceed the band of the amplifier 38, are cut by the amplifier 38 itself.

It is clear that, since the signal $E_{IN}(f)$ has very broad band, typically some THz, to proceed with the analysis it is necessary to subdivide the spectrum into sectors:

30
$$\tilde{E}_{IN}(f) = \sum_{n=-M}^{M} S_e(f - n\Delta f) e^{j\phi_n} .$$

Replacing this expression in (4), one obtains:

$$\tilde{I}_{AC}(f,T) \propto [\sum_{n=-M}^{M} S_{\varepsilon}(f - n\Delta f)e^{j\phi_n} * \sum_{n=-M}^{M} S_{\varepsilon}(f - n\Delta f)e^{j\phi_n}e^{j2\pi fT}] \cdot \tilde{H}'(f) \qquad (5)$$

According to the present invention, it is now possible to demonstrate that, under typical conditions of measurement and with commonly used amplifiers, thanks to
5 the ratio between the band B of the amplifier and the extension Δf of the spectral sectors, the expression (5) can be reduced to the diagonal form.

Considering, then, the convolution of two adjacent rectangular spectral sectors $r_1(f)$ and $r_2(f)$ of amplitude A
10 and band Δf:

$$r_1(f) * r_2(f) = A^2 f , \qquad 0 \le f \le \Delta f$$

Hereinafter the convolution of an elementary spectral sector with itself will also be considered:

$$r_1(f) * r_1(f) = -A^2 f + A^2 \Delta f , \qquad 0 \le f \le \Delta f$$

15 To evaluate the influence of the convolution of adjacent sectors on the photo-current, one can compute the ratio between the energies of the two preceding convolutions in the band of the amplifier 38:

$$SNR = \frac{E_{11}}{E_{12}} = \frac{\int_0^B [r_1(f) * r_1(f)]^2 df}{\int_0^B [r_1(f) * r_2(f)]^2 df} = \frac{\int_0^B [-A^2 f + A^2 \Delta f]^2 df}{\int_0^B [A^2 f]^2 df} = \frac{\int_0^B [A^4 f^2 - 2A^4 f\Delta f + A^4 \Delta f^2] df}{\int_0^B [A^4 f^2] df} ,$$

20

$$SNR = \frac{E_{11}}{E_{12}} = \frac{\left[\frac{A^4}{3} f^3 + A^4 f\Delta f^2 - A^4 f^2 \Delta f\right]_0^B}{\left[\frac{A^4}{3} f^3\right]_0^B} = \frac{\frac{A^4 B}{3}(B^2 + 3\Delta f^2 - 3\Delta f B)}{\frac{A^4 B^3}{3}} = \frac{(B^2 + 3\Delta f^2 - 3\Delta f B)}{B^2} .$$

Given that $k=\Delta f/B$, one easily computes:

$$SNR = 3k^2 - 3k + 1 .$$

This value is further divided by two, taking into account
25 that each sector has two adjacent sectors. The following

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Table 1 shows the value of SNR/2 thus computed as a function of the $\Delta f/B$ ratio.

$\Delta f/B$	SNR/2 (lin.)	SNR/2 (dB)
2	3.5	5.45
3	9.5	9.79
4	18.5	12.68
5	30.5	14.78
6	45.5	16.59
10	135.5	21.32

Tab. 1

It is readily apparent that for k=3 the value of SNR/2
5 already approaches 10 dB and exceeds 22 dB for k=10.

One can therefore conclude that, having appropriately chosen the ratio $k=\Delta f/B$, the prevalent contribution to the convolution in (2) is given by the sum of the convolutions of the homologous terms, and hence the current photo-
10 detected by the opto-electronic module 37 can be computed as:

$$\tilde{I}_{AC}(f,T) \propto [\sum_{n=-M}^{M} S_e(f-n\Delta f)e^{j\phi_n} * S_e(f-n\Delta f)e^{j\phi_n}e^{j2\pi fT}] \cdot \tilde{H}'(f) \qquad (6)$$

Using the result just obtained, only the diagonal terms of the equation (3) survive and the photo-current $I(v)$ takes
15 on the following form:

$$I(v) \propto \sum_{n=N}^{M} (a_n^2 + b_n^2)U_n^2 |S_e(v-n\Delta v)|^2 + \sum_{n=N}^{M} (a_n b_n)U_n^2 |S_e(v-n\Delta v)|^2 \left(e^{-j2\pi v\Delta\tau_n} + e^{j2\pi v\Delta\tau_n}\right)$$

(7)

The equation (7) is, according to the present invention, the most general expression of the photo-current
20 in the frequency domain that can be obtained without making hypotheses on the statistical nature of the PMD of the fibre being measured. Hereafter, the two cases of fibre

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with deterministic PMD and with random PMD shall be examined separately.

An optical fibre with a deterministic birefringence (for example, a polarisation-maintaining fibre) is characterised by constant DGD and PSP as a function of frequency. Consequently: $\Delta \tau_n = \Delta \tau$, $a_n = a$, $b_n = b$ are constant and the equation (7) is simplified in:

$$I(\nu) \propto (a^2 + b^2) \sum_{n=N}^{M} U_n^2 \left|S_c(\nu - n\Delta\nu)\right|^2 + ab\left(e^{-j2\pi\nu\Delta\tau} + e^{j2\pi\nu\Delta\tau}\right)\sum_{n=N}^{M} U_n^2 \left|S_c(\nu - n\Delta\nu)\right|^2 ,$$

i.e.,

$$I(\nu) \propto (a^2 + b^2)\left|S_{in}(\nu)\right|^2 + ab\left(e^{-j2\pi\nu\Delta\tau} + e^{j2\pi\nu\Delta\tau}\right)\left|S_{in}(\nu)\right|^2 .$$

A Fourier anti-transform directly yields the expression of the photo-current in the time domain:

$$I(T) \propto (a^2 + b^2)s_c(T) + ab[s_c(T - \Delta\tau) + s_c(T + \Delta\tau)] \qquad (8)$$

in which $s_c(T)$ is the source auto-correlation function, and corresponds to the Fourier anti-transform of $\left|S_{in}(\nu)\right|^2$.

The photo-current has three components: the source auto-correlation function and its replications translated about the two symmetric points $\pm\Delta\tau$. This well known result [1] is obtained with simple calculation within the proposed model.

Therefore, thanks to said characteristics the side lobes of the interferogram have the same shape as the central peak and are located in the two points $\pm\Delta\tau$, symmetrical with respect to the central peak.

The case of fibre with random birefringence is the more important one in practice and requires a more complicated mathematical treatment. The analysis is founded on the computation of the average value of the random process represented by the photo-current $I(\nu)$.

This computation has dual importance. First of all, it leads to a simple and elegant formal result represented by

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equation (9). Secondly, from the point of view of application to PMD measurement, this mathematical operation corresponds to a computation of averages of different measured interferograms, as will be shown hereafter,

5 allowing an experimental verification of the proposed model. From equation (7) one computes the statistical average $\langle . \rangle$ of the photo-current:

$$\langle I(\nu) \rangle = \left\langle \sum_{n=N}^{M} (a_n^2 + b_n^2) U_n^2 |S_e(\nu - n\Delta\nu)|^2 + \sum_{n=N}^{M} a_n b_n U_n^2 |S_e(\nu - n\Delta\nu)|^2 \left(e^{-j2\pi\nu\Delta\tau_n} + e^{j2\pi\nu\Delta\tau_n}\right) \right\rangle .$$

Taking into account the linearity of the statistical mean

10 and the fact that the random variables $\Delta\tau_n$ are independent from the random variables $a_n b_n$ and $\left(a_n^2 + b_n^2\right)$ (this is a direct consequence of the random nature of the birefringence of the fibre), one immediately obtains:

$$\langle I(\nu) \rangle = \sum_{n=N}^{M} \langle a_n^2 + b_n^2 \rangle U_n^2 |S_e(\nu - n\Delta\nu)|^2 + \sum_{n=N}^{M} \langle a_n b_n \rangle U_n^2 |S_e(\nu - n\Delta\nu)|^2 \left\langle e^{-j2\pi\nu\Delta\tau_n} + e^{j2\pi\nu\Delta\tau_n} \right\rangle.$$

15 Since the statistical average of the exponential of the random variables $\Delta\tau_n$ is their characteristic function $\Psi_{\Delta\tau_n}(\nu)$, the previous equation can be rewritten in the form:

$$\langle I(\nu) \rangle = \sum_{n=N}^{M} \langle a_n^2 + b_n^2 \rangle U_n^2 |S_e(\nu - n\Delta\nu)|^2 + \sum_{n=N}^{M} \langle a_n b_n \rangle U_n^2 |S_e(\nu - n\Delta\nu)|^2 \left(\Psi_{\Delta\tau_n}(-\nu) + \Psi_{\Delta\tau_n}(\nu)\right)$$

20 Moreover, for a given fibre, the characteristic functions $\Psi_{\Delta\tau_n}(\nu)$ and the statistical averages $\langle a_n b_n \rangle$ and $\langle a_n^2 + b_n^2 \rangle$ do not depend on frequency; i.e. they do not depend on the sum index n. Therefore, the previous equation is simplified as:

$$\langle I(\nu) \rangle = \langle a^2 + b^2 \rangle \sum_{n=N}^{M} U_n^2 |S_e(\nu - n\Delta\nu)|^2 + \langle ab \rangle \left(\Psi_{\Delta\tau}(-\nu) + \Psi_{\Delta\tau}(\nu)\right) \sum_{n=N}^{M} U_n^2 |S_e(\nu - n\Delta\nu)|^2 .$$

25 A Fourier anti-transform provides the statistical average of photo-current in the time domain:

$$\langle I(T)\rangle = \langle a^2 + b^2 \rangle s_c(T) + \langle ab \rangle s_c(T) * \left[f_{\Delta\tau}(-T) + f_{\Delta\tau}(T) \right], \qquad (9)$$

in which $f_{\Delta\tau}(T)$ is the probability density of $\Delta\tau$, and the asterisk indicates the convolution.

In this case, too, the photo-current is given by three contributions. The first term of equation (9) is linked to the properties of coherence of the optical source, and it is represented by a peak located in the origin of the times axis. The second and third term correspond to two symmetrical lateral lobes and contain all the information required to measure the PMD. The expression of the average photo-current, in spite of the symmetry about a peak in $T = 0$, is very different from a Gaussian, due to the presence of the side lobes constituted by the convolution of $s_c(T)$ with the probability density of the differential group delay $f_{\Delta\tau}(T)$. Since it is assumed that the coherence time of the source (i.e. the width of the central peak) is negligible relative to the average DGD of the fibre, the two side lobes represent approximate measurements of the probability density of the DGD of the fibre. The quality of this approximation depends, as stated, on the coherence time of the source used, and can be improved by means of an appropriate de-convolution of the interferometric diagram measured with the auto-correlation function of the source itself $s_c(T)$ (this function can be measured separately by directly connecting the optical source to the interferometer). Lastly, it can be stated that equation (9) is a generalisation of equation (8) if one only considers that the probability density of the DGD of a fibre with systematic birefringence is a Dirac function δ.

Therefore, thanks to this characteristic the measurement of PMD with interferometric technique is

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conducted not with a Gaussian interpolation of the
interferogram, but rather by analysing at least one of the
side lobes of the interferogram, considered, according to
the present invention, as an approximate measurement of the
5 probability density of the DGD associated with the PMD of
the optical fibre 11.

The propagation model according to the present
invention was tested by means of simultaneous PMD
measurements using both the interferometric method,
10 described in the present embodiment, and the method, also
known, of JME or Jones Matrix Eigenanalysis.

The tested fibre (50 km of coil wrapped single mode
conventional fibre) was placed in a thermal chamber at
temperatures varying from about 2°C to about 60°C at 5°C
15 steps. After each variation, the fibre was allowed to
stabilise before conducting the interferometric and
polarimetric measurements. Thereby, over several days, 15
interferograms and 15 DGD measurements with JME method
(each constituted by 91 points) were acquired. The data
20 were then processed with the following procedure:

- the mean of the interferograms was computed after they
  were normalised;

- said mean was compared with two symmetrical replications
  of the DGD probability density computed from the JME
25 data.

Note that the first processing operation is suggested
directly by the interpretation of the interferograms as
probability density and corresponds to the computation of
the mean photo-current as shown in equation (9).
30 From Fig. 4, which shows the results of the measurements,
the good agreement between the results is readily apparent.

In particular, from the results of the measurements, it
is readily apparent that the central peak of the

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interferogram must be neglected because it depends only on the characteristics of coherence of the source and not on the PMD of the fibre.

The result obtained, according to the present
5 invention, attributes a new physical meaning to the interferometric curves, particularly useful for measurement activities.

Obvious modifications or variations are possible to the above description, in the dimensions, shapes, materials,
10 components, circuit elements, connections and contacts, as in the details of the circuitry and of the illustrated construction and of the method to be implemented, without thereby departing from the spirit of the invention as specified by the claims that follow.

15

CLAIMS

1. Method for measuring the polarisation mode dispersion of
an optical fibre applying an optical signal to a first end
of the fibre (11) and coupling a second end of the fibre
5   (111) to an interferometer (25), said method comprising the
step of:
- generating by means of said interferometer (25) at least
one interferogram comprising at least a central peak and
two side lobes having a determined information content;
10 and being characterised by the steps of
- processing said interferogram in such a way as to measure
the information content of at least one of said two side
lobes;
and
15 - determining the polarisation mode dispersion of the fibre
associating to said measurement of said information content
a probability density function representative of the
polarisation mode dispersion (PMD) of the fibre in the form
of differential group delay.

20 2. Method as claimed in claim 1 characterised in that said
step of determining the polarisation mode dispersion
comprises the step of
- computing the deconvolution of said at least one side
lobe with said central peak so that said deconvolution
25 corresponds to the probability density of the differential
group delay determined by the PMD of the fibre.

3. Method as claimed in claim 1 or 2 characterised by the
additional step of
-   determining   an   average   of   measurements   of   said
30 information content whereto said probability density is to
be associated.

4. Method as claimed in any of the previous claims,
characterised in that said information content comprises a

single numeric value determined by the position of said at least one side lobe in the interferogram.

5. Method as claimed in claims 1 through 3 characterised in that said information content comprises a plurality of
5 values determined by the position of said at least one side lobe in the interferogram.

6. Computer product able to be directly loaded in the internal memory of an electronic measuring device and comprising portions of software code to implement the
10 method as claimed in any of the claims from 1 to 5 when the product is run on said electronic device.

7. System for measuring the polarisation mode dispersion of an optical fibre, comprising

- an optical source (21) able to generate an optical signal
15 to be injected into the fibre (11);

- an interferometer (25) associated to the fibre and able to generate an interferogram comprising at least a central peak and two side lobes having a determined information content;

20 characterised by

- a device (27) connected to said interferometer and able to

   - process said interferogram in such a way as to measure the information content of at least one of said
25   side lobes; and

   - determining the polarisation mode dispersion of the fibre associating to said measurement of said information content a probability density function representative of the polarisation mode dispersion
30   (PMD) of the fibre in the form of differential group delay.

8. System as claimed in claim 7, characterised in that said device (27) comprises

- a first module able to compute the deconvolution of said
at least one side lobe with said central peak so that said
deconvolution corresponds to the probability density of the
differential group delay determined by the PMD of the
5 fibre.

9. System as claimed in claim 7 or 8, characterised in that
said device comprises

- a second module able to determine an average of
measurements of said information content whereto said
10 probability density is to be associated.

10. Device for measuring the polarisation mode dispersion
of an optical fibre into which optical signals have been
injected, comprising

- an opto-electronic module (37) able to convert the
15 optical signals into electrical signals;

- a display device (35) able to generate an interferogram
comprising at least a central peak and two side lobes
having a determined information content; characterised by

- a control unit (30) able to

20   - measure the information content of at least one of
          said two side lobes; and

          - determining the polarisation mode dispersion of the
          fibre associating to said measurement of said
          information content a probability density function
25   representative of the polarisation mode dispersion
          (PMD) of the fibre in the form of differential group
          delay.

11. Device as claimed in claim 10, characterised in that it
comprises

30 - a first program module able to compute the deconvolution
of said at least a side lobe with said central peak so that
said deconvolution corresponds to the probability density

of the differential group delay determined by the PMD of the fibre.

12. Device as claimed in claim 10 or 11, characterised in that it comprises

5 - a second program module able to determine an average of measurements of said information content whereto said probability density is to be associated.
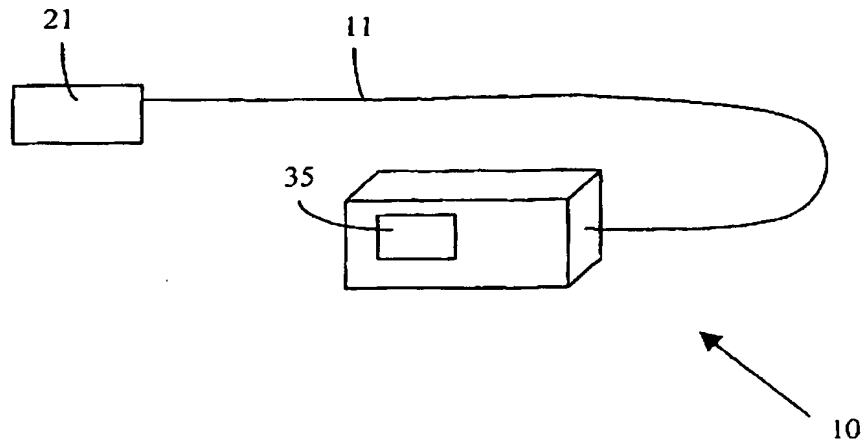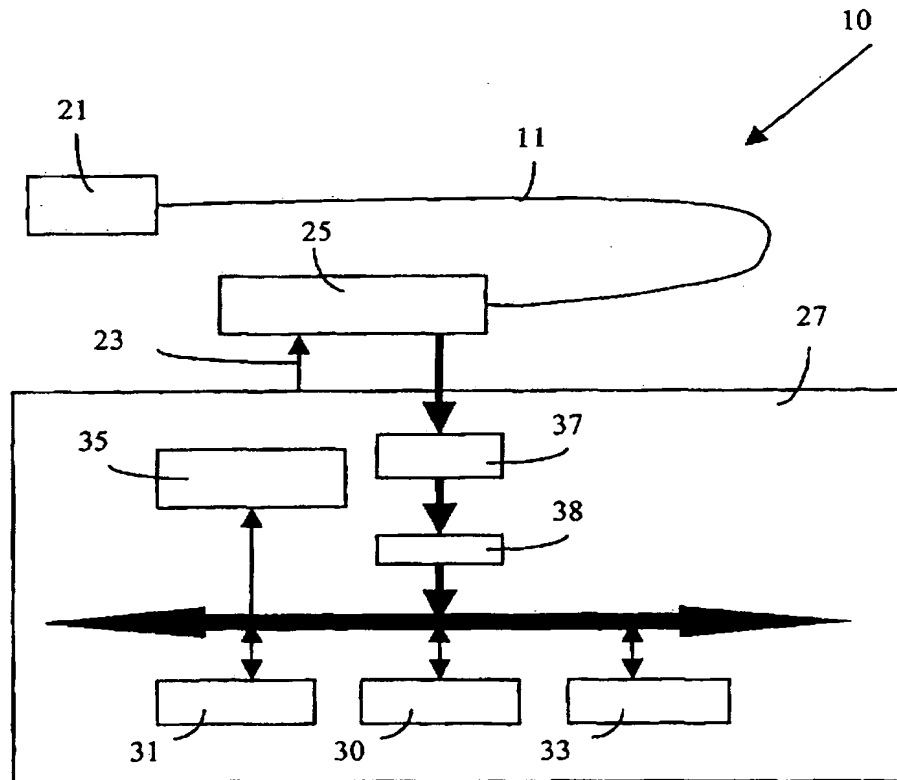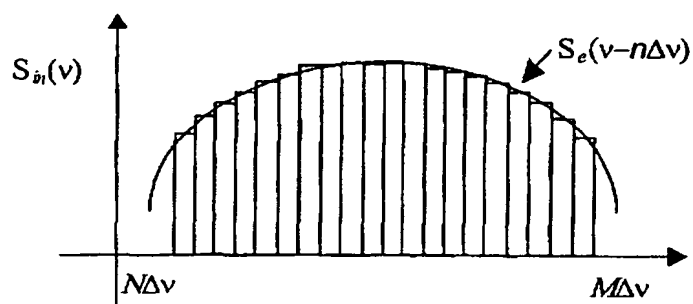
1/2

Fig. 1

Fig. 2

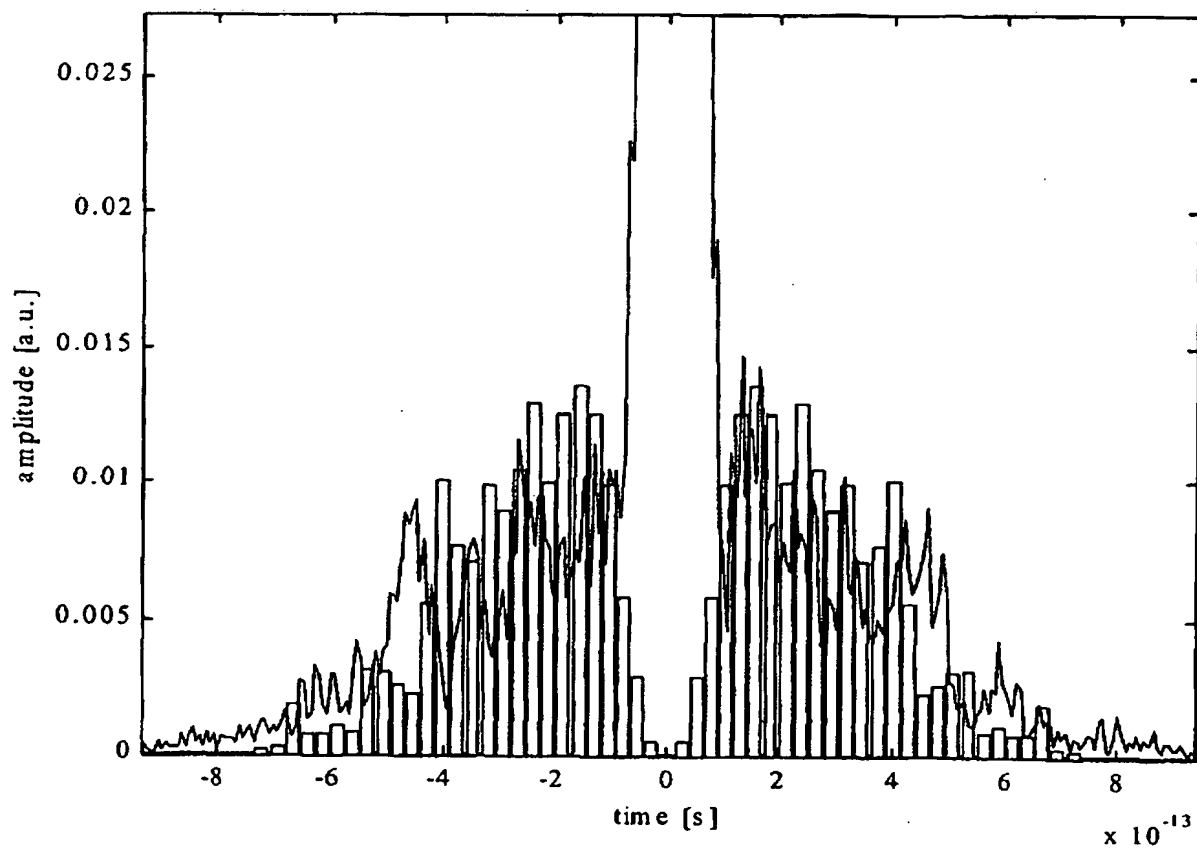Fig. 3

Fig. 4

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   G01M11/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7   G01M   H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 712 704 A (P. MARTIN ET AL.) 27 January 1998 (1998-01-27) the whole document	1,6,7,10
A	US 5 852 496 A (N. GISIN ET AL.) 22 December 1998 (1998-12-22) the whole document	1,6,7,10
A	US 4 556 314 A (J. STONE) 3 December 1985 (1985-12-03) the whole document	1,6,7,10
A	US 6 271 922 B1 (H. BÜLOW ET AL.) 7 August 2001 (2001-08-07) the whole document	1,6,7,10
	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
18 November 2003	25/11/2003

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Van Assche, P

Form PCT/ISA/210 (second sheet) (July 1992)

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	WO 96 36859 A (T.L. VOOTS) 21 November 1996 (1996-11-21) the whole document ---	1,6,7,10
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